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Procedia Engineering 34 (2012) 556 – 561

Procedia Engineering

www.elsevier.com/locate/procedia

9th Conference of the International Sports Engineering Association (ISEA)

If motion sounds: Movement sonification based on inertial sensor data

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Accepted 02 March 2012

Abstract

Within last years, movement sonification turned out to be an appropriate support for motor perception and motor control that can display physical motion in a very rich and direct way. But how should movement sonification be configured to support motor learning? The appropriate selection of movement parameters and their transformation into characteristic motion features is essential for an auditory display to become effective. In this paper, we introduce a real-time sonification framework for all common MIDI environments based on acceleration and orientation data from inertial sensors. Fundamental processing steps to transform motion information into meaningful sound will be discussed. The proposed framework of inertial motion capturing, kinematic parameter selection and possible kinematic acoustic mapping provides a basis for mobile real-time movement sonification which is a prospective powerful training tool for rehabilitation and sports and offers a broad variety of application possibilities.

Keywords: Movement sonification; inertial sensor; data representation; motor learning; acoustic feedback

1. Introduction

In current training scenarios, the process of learning movement techniques mainly relies on visual learning strategies. However, research showed that the stimulation of additional sensory systems during training can enhance motor control and motor learning within both sports and medical applications. Especially auditory feedback is considered to be effective for motor control and motor learning [1, 2]. But in contrast to visual feedback, which is explored very well, there are only a few studies on efficient

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doi:10.1016/j.proeng.2012.04.095

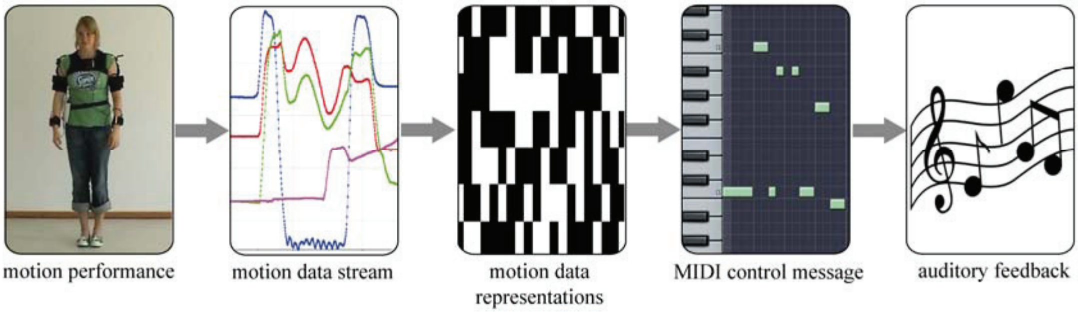

Fig. 1. Schematic overview of the proposed sonification framework consisting of motion capturing procedures, motion data processing procedures and the final auditory display

transformation of biological motion into auditory feedback [3] and therefore it remains unclear how to provide and process the captured data to display sound in an effective and accurate way. Finding an efficient movement sonification strategy can hence offer various new possibilities for training applications such as mobile devices being worn directly attached to the actor's body within the athlete's equipment or clothes. For this, it is important to retrieve relevant motion aspects out of the present motion capture data set and transform them into significant motion features. Those features should reflect specific motion structures such as singularity within motion patterns or motion range. Different representations of kinematic motion data (spherical and Cartesian point data or joint angles) that may help to maintain the essentials of a specific movement are discussed in this paper. Furthermore, possibilities to map kinematic motion data onto sound using the standard MIDI protocol will be described. A sonification framework, see Fig. 1, will be developed on a sample application for rehabilitation of the upper extremities.

2. Movement sonification with inertial sensors

2.1. General information

Sonification has been introduced for various application areas and has been used in various fields of science and life over the last two decades [3]. To sonify human movements, kinematic and dynamic data representations have been derived from several motion capture devices, for example forces from a force measurement plate [1] or motions of a German wheel from a simple magnetometer [4]. In our framework, up to ten inertial MTx motion trackers of XSens technologies are used to capture everyday movements of a subject such as arm rotation, grasping and drinking as they can occur in rehabilitation scenarios. Since inertial sensors are of comparably small size and easy to use they are well-suited for mobile applications. Directly attached to the actor's body within the athlete's equipment or clothes they can be part of a mobile training device, which provides auditory feedback during rehabilitation and training.

Auditory and visual stimuli are perceived as originating from a single event even with an intermodal delay up to about t_{IM} =100ms and multisensory areas are addressed within the central nervous system [5]. As a consequence of these neural mechanisms we set a benchmark at t_{max}=30ms assuring that subjects can perceive auditory display in real-time and merge it with feedback of other modalities during motor performance. Functional background of movement sonification had been explored by Scheef et al. [6].

2.2. Inertial sensors and sensor arrangement

Inertial sensors offer detailed motion information on acceleration and rotational velocity within their measurement range. Positional data as being available in optical motion capture systems cannot be determined directly. However, inertial sensors can be used in everyday environments and under daylight conditions without complicated setup procedures. That makes them favorably for future auditory training sessions independently from local and static reference systems. In the present study, the sensors' acceleration and orientation data are mainly used. However, a transformation of raw and processed inertial data into further data representations that are explained in Section 3 might be reasonable.

Inertial sensors can be placed freely on a person's body attached to either bones, joints or limbs. How to place the sensors mainly depends on the data representation and the selected motion features chosen for further processing steps. We attach each sensor in line with the bones to the actor's body and determine joint angles using neighboring sensor's orientations. Joint angles are used to compute joint positions using predefined lengths of the subject’s limbs by forward kinematics as shown in Fig. 2.

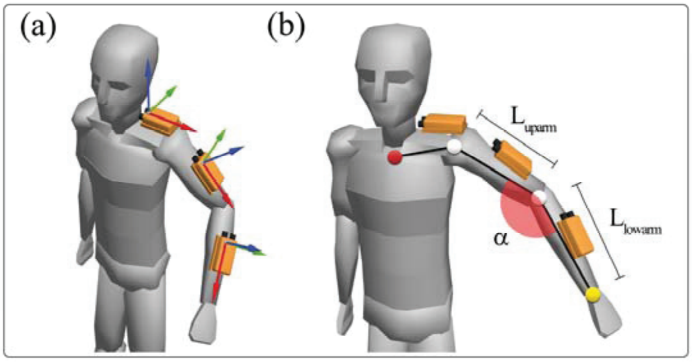

Fig. 2. (a) Sensor orientation as used in this paper for the upper extremity. (b) The position of each joint is computed using the forward kinematics principle. For example, with the given lengths L_{uparm} and L_{lowarm} for upper and lower arm and the enclosed angle α between both limbs defined by the sensors’ orientation, the position of the wrist can be determined (kinematic chain)

3. Data representations for movement sonification

Various possibilities exist to process inertial motion data for further applications of movement sonification as well as motion classification or analysis. Here we discuss three popular kinds of data representations used in different application fields [7, 8] and discuss their potential efficiency within the movement sonification framework. Fig. 3 shows our definition for the coordinate systems of those three data representations which correspond to sensorimotor reference frames in humans [9].

3.1. Cartesian coordinates

Using a simple forward kinematics approach, positions of every joint are easily computable as shown in Fig. 2b. Given the length and orientation of each limb which can be represented by the sensor's orientation with the sensors in line with the bones, the Cartesian point coordinates of every joint within a defined coordinate system can be determined by the defined three orthogonal axes $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{z}$ [8]. Every point $\boldsymbol{P}$ can be defined by a three dimensional vector $\boldsymbol{v}$ so that $P = v\,(x_P, y_P, z_P)$ with $\boldsymbol{x_P}$, $\boldsymbol{y_P}$ and $\boldsymbol{z_P}$ being the value along the corresponding axis. However, perception of human motion is obviously not based on an absolute representation of joint positions but on a continuous change of the relative positions, (biological motion perception, e.g. described by [10]). For example, moving the hand along the horizontal axis is not only equivalent to a change in the hand's position along this axis, but also with a change of the position and orientation of further joints. This information cannot be included within a Cartesian data representation which uses only biological information on one selected joint, see Fig. 3a.

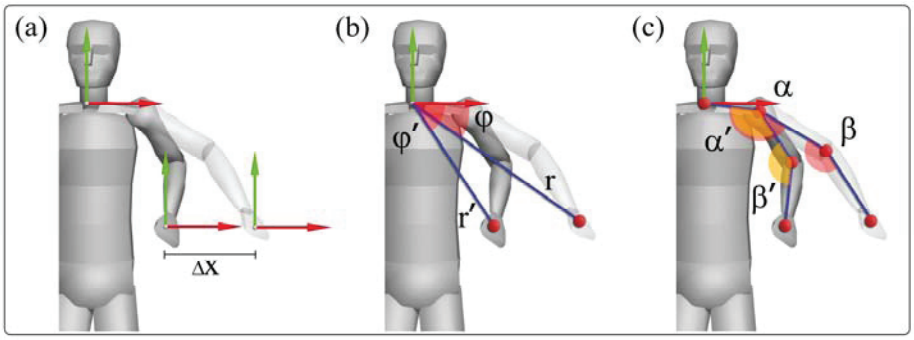

Fig. 3. Defined coordinate systems for (a) Cartesian and (b) spherical coordinates and (c) angular representations. Changes in the position of a joint are differently displayed within each coordinate system: moving the wrist along a horizontal line evokes a change in the x-coordinate data for Cartesian data, a change of the azimuth angle φ and the radius for spherical coordinates and at least two angles at shoulder and elbow joint

To display the full characteristics of a biological movement, information on further joints is necessary.

3.2. Spherical coordinates

Another data representation which is closer related to the principle of human motor control are spherical coordinates. Here, the position of joints are defined by two angles: azimuth φ which represent a joint's position on the horizontal axis and inclination angle θ which represents the elevation of a joint and the radius r. The radius represents the distance of a joint to the origin of the coordinate system, which is located in the middle of the actor's body in our case. Every point P can be defined by a three dimensional vector v so that $P = v\ (r,\theta,\varphi)$. Angular movement features represented within spherical coordinates are closer to internal human motor control and can also yield more detailed information during sonification. Research showed that the central nervous system controls arm movements in similar ways as they are represented by spherical coordinates [11, 12]. For example, moving the wrist along the horizontal axis would not only represent a motion along the horizontal axis but also include a decrease of the hand's distance to the body center and hence contain information about enclosed angle between elbow and radius. It is then possible to display essential movement information by only one joint, see Fig. 3b.

3.3. Angular representations

Angular representations are only based on angular movement features and do not involve any positional information, see Fig. 3c. To display the motion of a subject´s wrist it is necessary to include each degree of freedom of the related joints within the kinematic chain. To display for example the motion of a subject's wrist, all angles in shoulder, elbow and hand have to be displayed which produces a very rich sound of much more detailed information than for example in spherical coordinates. However, the complexity of an angular representation for several joints with two or three degrees of freedom each is quite high making motion feedback thus very difficult to perceive and understand.

4. Transforming motion data into sound

Finding the right data representation for a sonification strongly depends on the sonification purpose, the performed motion and the intended sound mapping. As they are satisfying with respect to both accuracy and amount of necessary data, we use spherical coordinates for the next step, the transformation of motion features into sound. To display selected motion data streams as sound, we use Miller Puckette's open source software *Pure Data* (**PD**) for electronic sound creation. PD gives the opportunity to send MIDI control messages that produce and influence sound within MIDI sound systems. It has been used for MIDI movement sonification before, for example to display rowing motion [13]. MIDI offers a consequent and well-defined way to control and generate sound which makes it convenient to map motion data onto sound. For example, control messages can influence and change sound properties easily. Furthermore, the timbre of a sound can easily be changed before or even during a performance with so called “sound programs” to simulate different sounds and instruments, see Fig. 4.

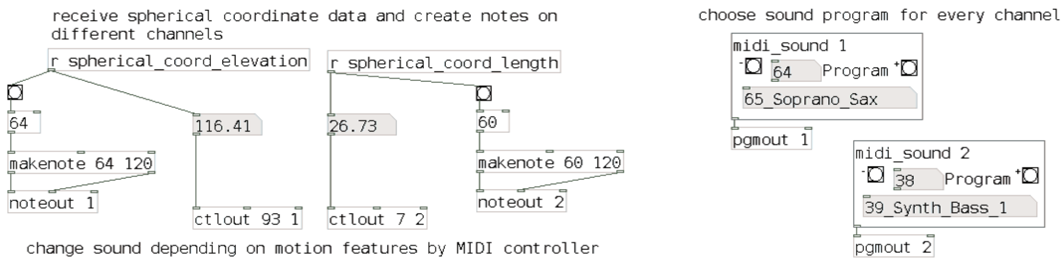

Fig. 4. Sample PD patch to control sound by incoming motion data. Spherical motion information (spherical_coord_elevation and spherical_coord_length) is constantly sent to create notes by the commands makenote and noteout. Sound change information is triggered using MIDI control messages ctlout of number 93 (chorus) and 7 (volume)

The coarse resolution of MIDI control messages consists of 128 steps to trigger sound properties. The broad range of standard MIDI commands leaves several possibilities to map motion features onto the auditory feedback such as velocity, pitch height or timbre. For example, every time the maximal motion velocity occurs within motion performance, the corresponding MIDI controller could be of maximal value 127 while having no motion velocity at all, the MIDI controller would be of minimal value 0. Fig. 4 shows a sample PD patch that creates MIDI notes and sends MIDI control messages to change sound properties in accordance with the corresponding motion feature. Here, MIDI controllers 93 and 7, which represent chorus and volume, are constantly triggered by the motion data so that the resulting sound changes in real-time. Many other MIDI controllers can be accessed in the same way, leading to different sound results according to their MIDI specification [14]. MIDI properties that can be used to modify sound are for example: attack and release time, timbre, tone frequency, velocity or sound effects as reverb and echo. Sound mappings that have already been realized for sonification purposes are listed in [3].

Various upper body motions by different motion actors have been sonified in first experimental studies: large and spacious movements such as arm rotation or throwing as well as small and spatially centered motions such as drinking, grasping or writing. All Motions can be displayed well in real-time under different selected sound properties and sound mappings while maintaining characteristics of each motion and for a time period of more than two hours. For example, by mapping motion velocity onto volume, throwing will be perceived as getting much louder than drinking. In general, users reported to be able to adapt themselves quickly to the auditory feedback. Detailed experiments on motion identification and motor learning with a broad range of users are conducted at the moment.

5. Conclusion

We gave an example on how to use inertial motion capture data to produce a mobile and locally independent movement sonification based on general MIDI specifications for upper body motion. By using spherical coordinates we furthermore introduced an appropriate coordinate system which displays natural human movement patterns well while using only sparse information. Such a framework seems to be suitable for the auditory coding of gross motor movements of the upper limbs that might be easily perceivable.

The effects of different sound and parameter mappings on perception and motor control are investigated in ongoing studies. The results can show how to map motion data into sound for an efficient display of movement characteristics and the course of a motion. The integration of movement sonification into sport and rehabilitation will offer a broad range of supporting applications on motor training in the future.

Acknowledgments

We would like to thank the European Union for financially supporting this research as project W2-80118660 within the European Fond for regional development (EFRE).

References

[1] Effenberg, A. O. (2005). Movement Sonification: Effects on perception and action. *IEEE Multimedia*, 12(2), Pages 53-59.
[2] Effenberg, A. O., Weber, A., Mattes, K., Fehse, U. and Mechling, H. (2007). Motor Learning and Auditory Information: Is Movement Sonification efficient? *Journal of Sport & Exercise Psychology*, 29, Page 66.
[3] Dubus, G. and Bresin, R. (2011). Sonification Of Physical Quantities Throughout History: A Meta-study Of Previous Mapping Strategies. *Proceedings of the 17th International Conference on Auditory Display*. Budapest, Hungary.
[4] Hummel, J., Hermann, T., Frauenberger, C. and Stockman, T. (2010). Interactive sonification of German wheel sports movement. *Human Interaction with Auditory Displays – Proceedings of the Interactive Sonification Workshop*, Pages 17–22.
[5] Stein, B. E. and Meredith, M. A. (1993). *The Merging of the Senses*. Cambridge: MIT Press.
[6] Scheef, L., Boecker, H., Daamen, M., Fehse, U., Landsberg, M.W., Granath, D., Mechling, H. and Effenberg, A. O. (2009). Multimodal motion processing in area V5/MT: Evidence from an artificial class of audio-visual events. *Brain Research*, Volume 1252, Pages 94-104.
[7] Yen B. L. and Huang T. S. (1983). Determining 3-D motion and structure of a rigid body using the spherical projection. *Computer Vision, Graphics, and Image Processing*, Volume 21, Issue 1, Pages 21-32.
[8] Zhou H. and Hu H. (2005). Inertial motion tracking of human arm movements in home-based rehabilitation. *Proceedings of IEEE international conference on mechatronics and automation*. Niagara Falls, Ontario, Canada, Pages 1306–1311.
[9] Shadmehr, R. and Wise, S. P. (2005). The computational neurobiology of reaching and pointing: A foundation for motor learning. *Computational Neuroscience*.
[10] Troje, N. F., Westhoff, C. and Lavrov, M. (2005). Person identification from biological motion: Effects of structural and kinematic cues. *Perception & Psychophysics*, 67(4), Pages 667-675.
[11] Graziano, M., Taylor, C. and Moore, T. (2002). Complex Movements Evoked by Microstimulation of Precentral Cortex, *Neuron*, Volume 34, Issue 5, Pages 841-851.
[12] Schmitz, G., Bock, O., Grigorova, V. and Ilieva, M. (2010). Adaptation of eye and hand movements to target steps of different size. *Experimental Brain Research*, 203 (2), Pages 479-484.
[13] Henkelmann, C. (2007). Improving the Aesthetic Quality of Realtime Motion Data Sonification Bonn. *Technical Report number CG-2007-4*. University of Bonn.
[14] Rothstein, J. (1992) *MIDI: a comprehensive introduction*. Oxford University Press, Oxford.